

# Early Thermalization at RHIC ?!

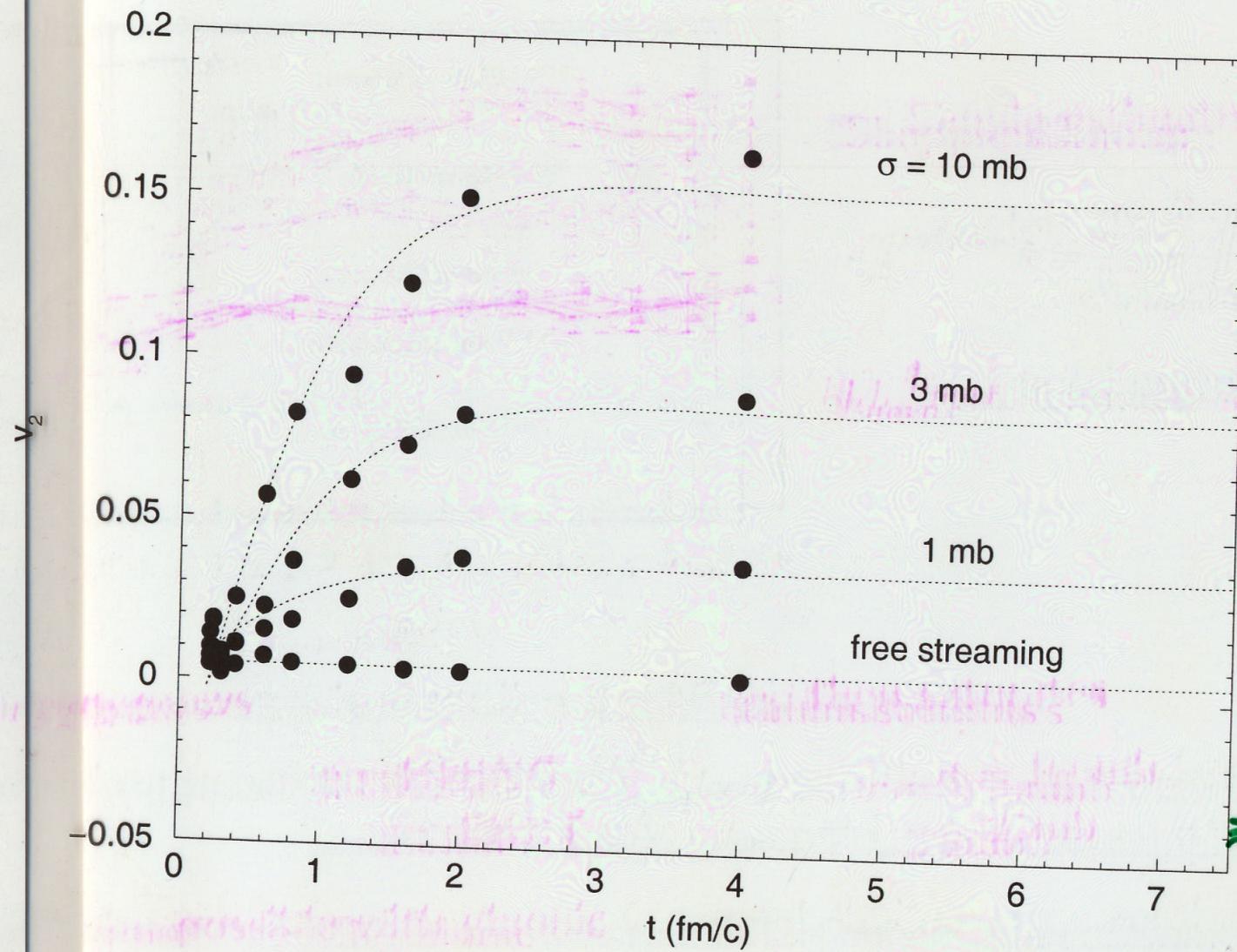
Peter Kolb + U. Heinz, Ohio State U.

in collaboration with P. Huovinen

- Radial and elliptic flow - theoretical characteristics
- RHIC spectra vs. hydrodynamics
- What does this all mean? A challenge for microscopic theories

In fact, a lot of rescattering!

Elliptic flow requires rescattering:



B.Zhang, M.Gyulassy, C.M.Ko, PLB 455 (1999) 45

$\gtrsim 30 \times \sigma_{\text{QCD}}$ !  
 $\gtrsim 10$  times  $\sigma_{\text{QCD}}$ !

## Relativistic Hydrodynamics

Conservation of energy, momentum and baryonnumber

$$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu j^\mu = 0$$

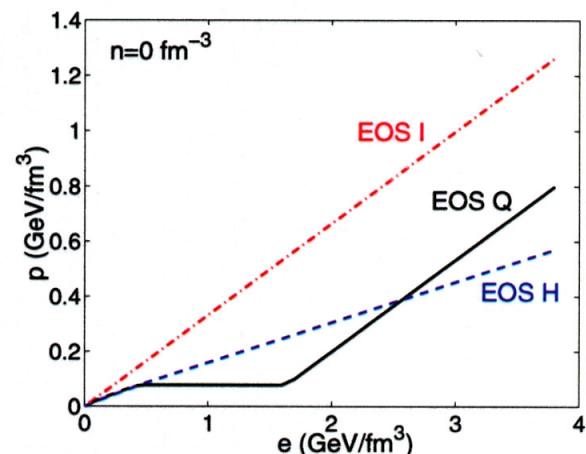
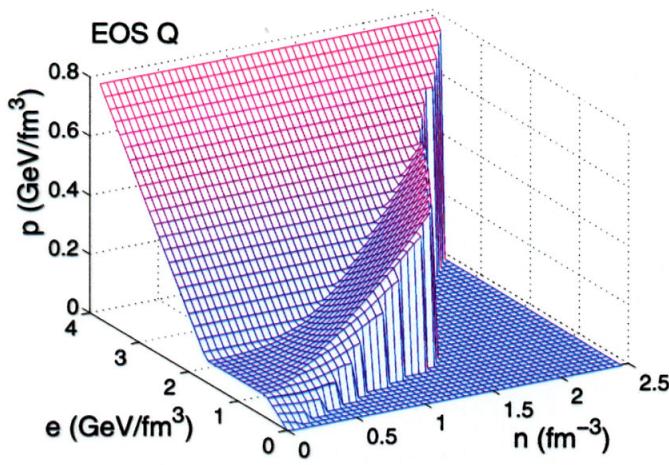
with energy momentum tensor:

$$T^{\mu\nu}(x) = (e(x) + p(x)) u^\mu(x) u^\nu(x) - g^{\mu\nu} p(x)$$

and baryon current:  $j^\mu(x) = n(x) u^\mu(x)$

## Equations of state

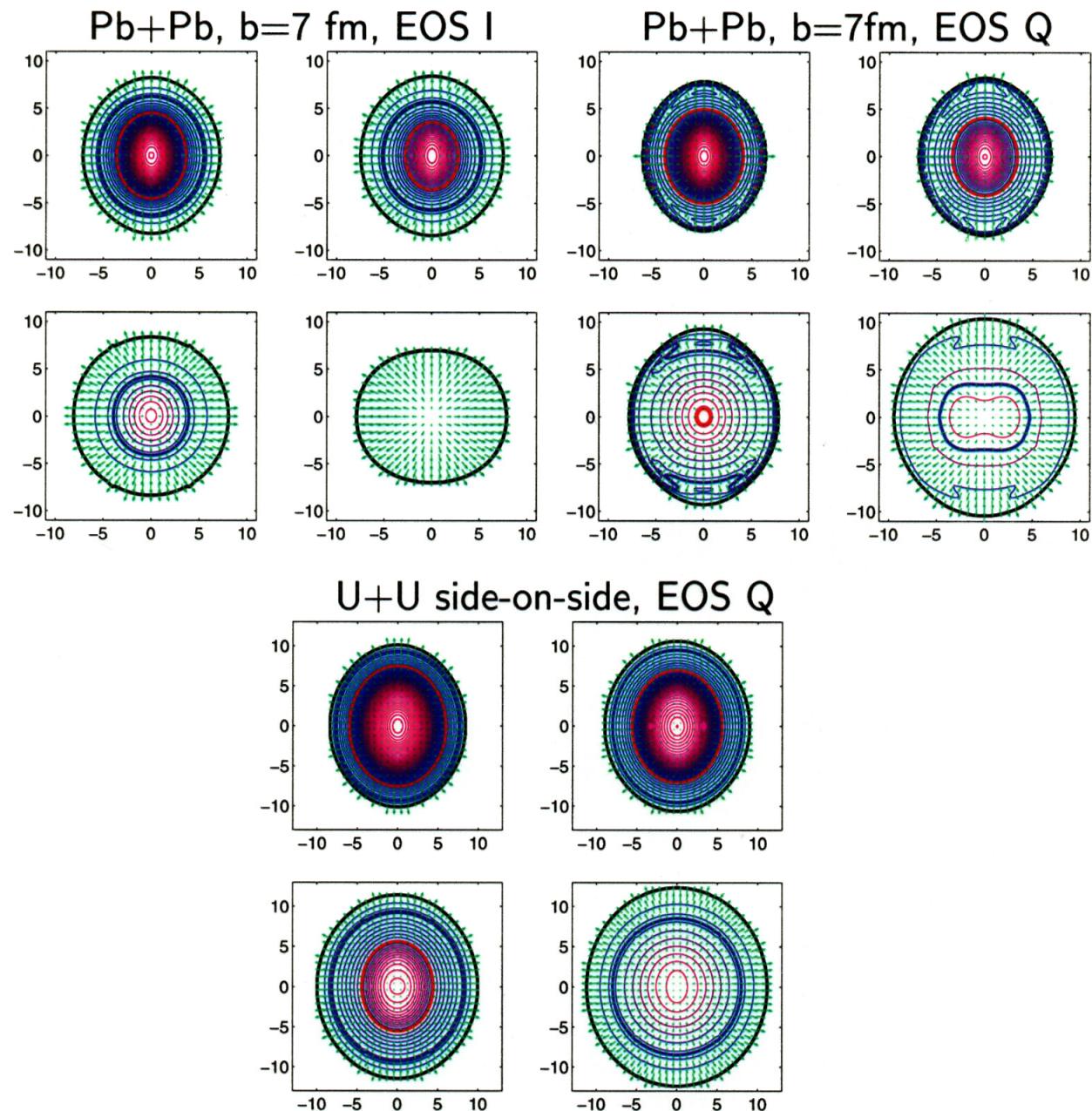
- **EOS I:** ultrarelativistic ideal gas,  $p = \frac{1}{3} e$
- **EOS H:** massive, interacting gas of hadrons,  $p \sim 0.15 e$
- EOS Q: Maxwell construction between **EOS I** and **EOS H**
  - critical temperature  $T_{\text{crit}} = 0.16 \text{ GeV}$
  - bag constant  $B^{1/4} = 0.23 \text{ GeV}$



## Evolution of energy density,

$$T_0 \approx 500 \text{ MeV} \quad \omega_{\text{equ}} = 0.4 \text{ fm}/c$$

snapshots at  $\tau = 3.2, 4.0, 5.6$  and  $8.0 \text{ fm}/c$  after initialization



Initial conditions:  $s(\vec{r}, \tau_0) = x s_{SC}(\vec{r}, \tau_0) + (1-x) s_{WN}(\vec{r}, \tau_0)$

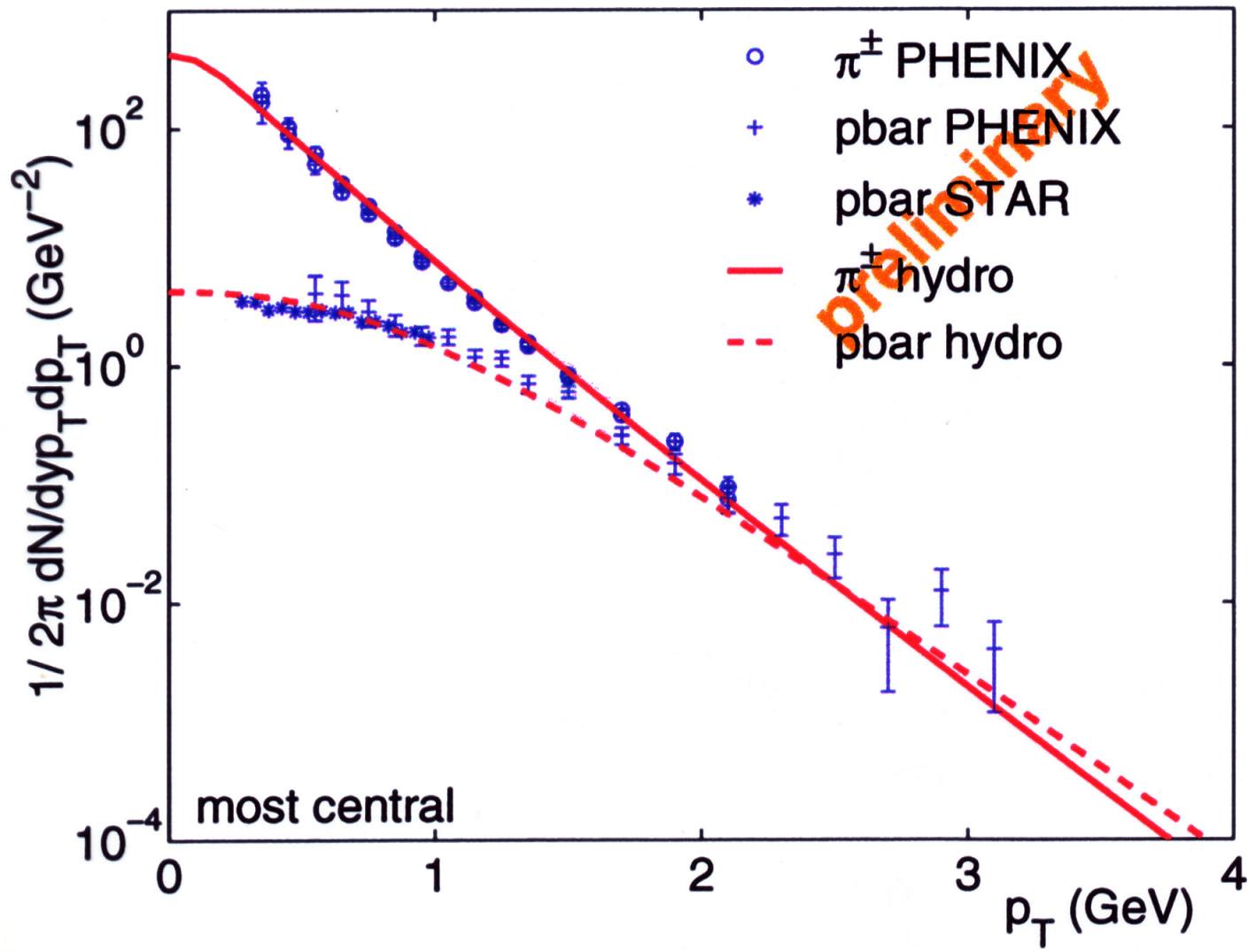
 $x = 0.25$ 
 $\tau_0 = 0.6 \text{ fm}/c$ 
 $E_0 = \Sigma(\vec{r}=0, \tau_0) = 21.4 \text{ GeV/fm}^3 \text{ at } b=0$ 
 $n_0 = 0.2 \text{ fm}^{-3} \Rightarrow \bar{P}/p = 0.6 \text{ at } T_{had}$ 
 $T_0 = 323 \text{ MeV} \text{ at } b=0$ 

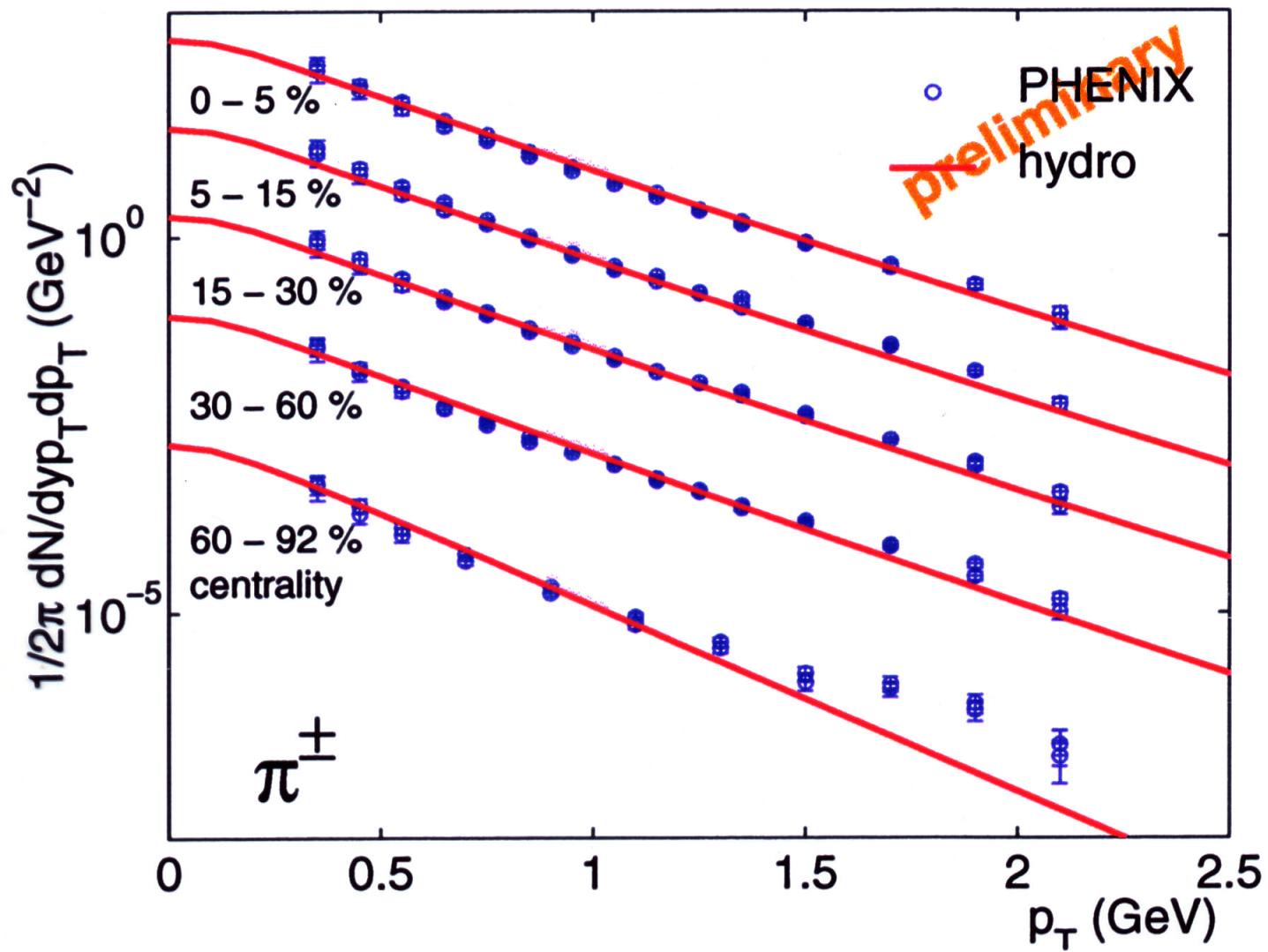
Decoupling conditions:  $T_{dec} = 128 \text{ MeV}$   
 $\langle n_\perp \rangle \approx 0.6 c \text{ at } b=0$   
 $\mu_B \approx 70 \text{ MeV}$   
 $\gamma_p = \gamma_{\bar{p}} = 2.55 = \epsilon$   $^{120 \text{ MeV}/128 \text{ MeV}}$

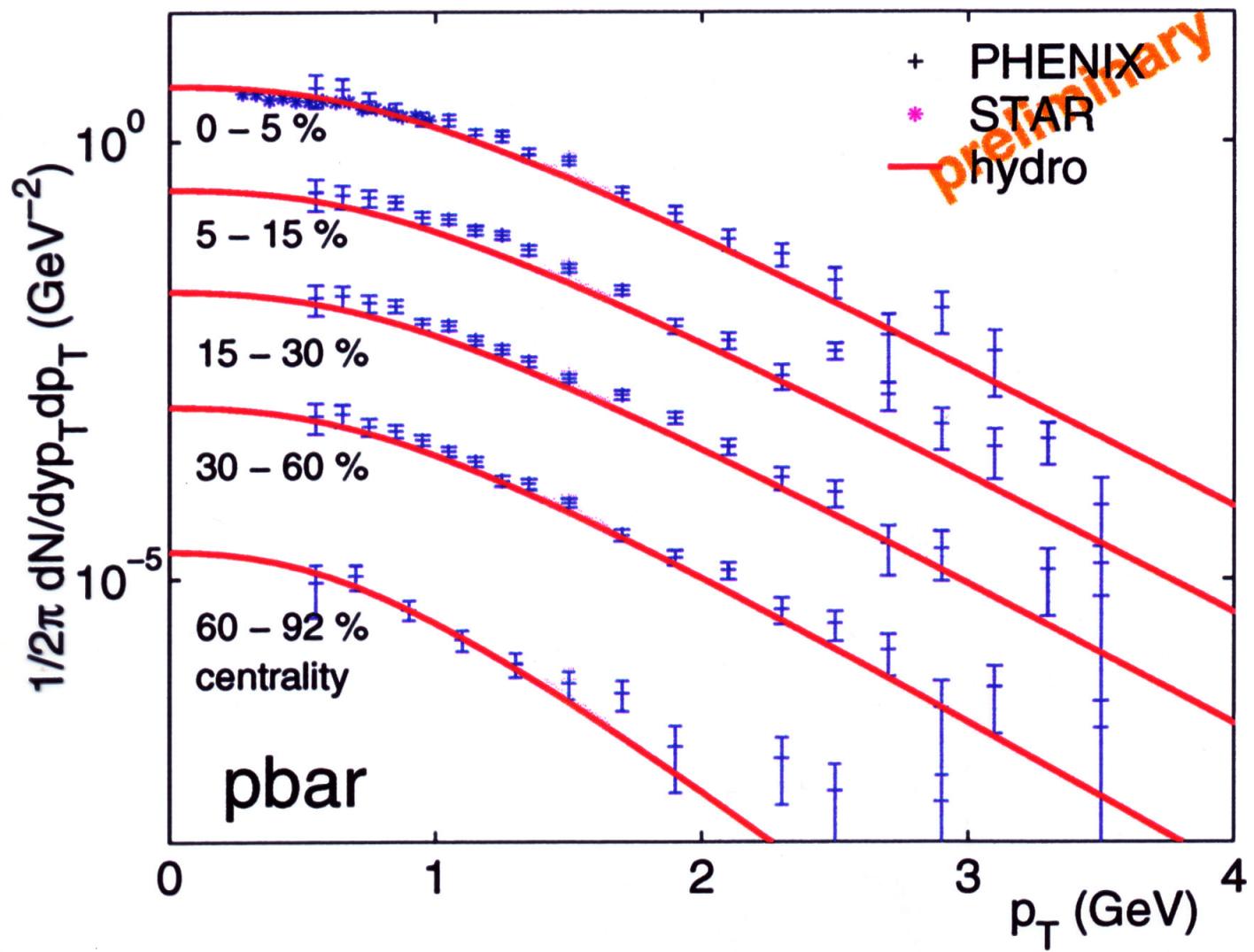
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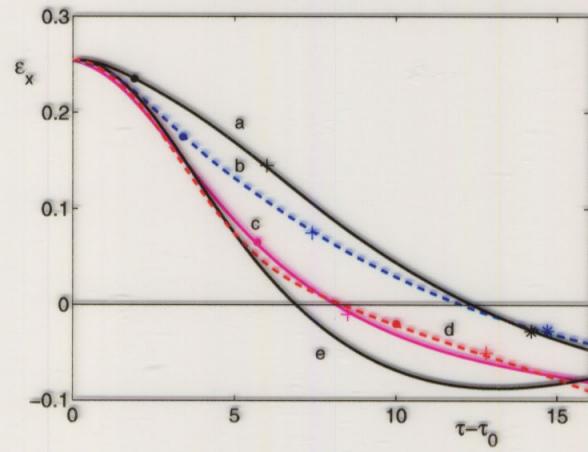




## Evolution of Pb+Pb, $b=7$ fm

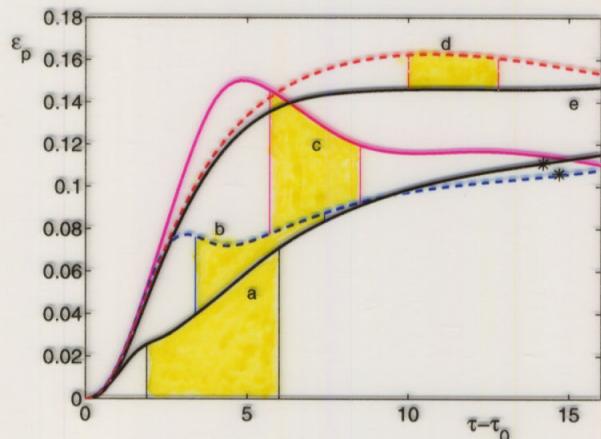
for various initial energies

$a \approx 9.0, b \approx 25, c \approx 175, d \approx 25000 \text{ GeV/fm}^3; e \approx \text{ideal gas limit}$



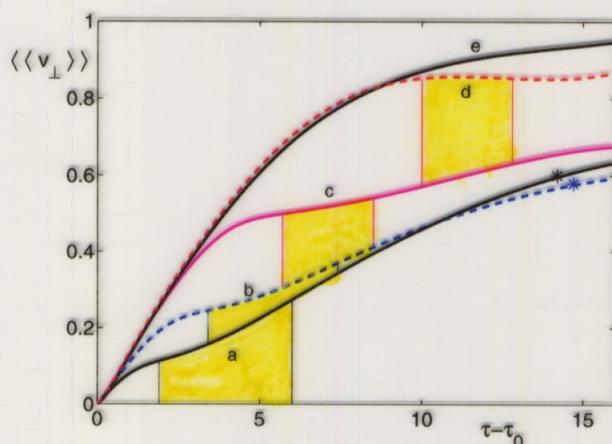
spatial asymmetry

$$\epsilon_x = \frac{\langle\langle y^2 - x^2 \rangle\rangle}{\langle\langle y^2 + x^2 \rangle\rangle}$$



momentum anisotropy

$$\epsilon_p = \frac{\langle\langle T^{xx} - T^{yy} \rangle\rangle}{\langle\langle T^{xx} + T^{yy} \rangle\rangle}$$



radial flow

$$\langle\langle v_{\perp} \rangle\rangle = \frac{\left\langle\left\langle \sqrt{v_x^2 + v_y^2} \right\rangle\right\rangle}{\langle\langle \gamma \rangle\rangle}$$

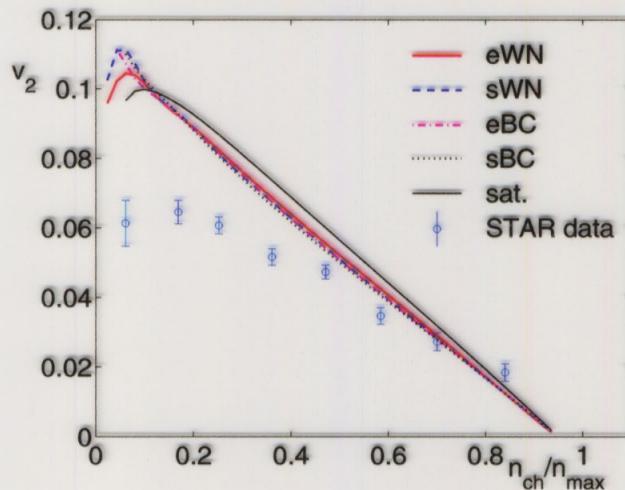
P.Kolb et al., PRc 62, 054909 (2000)

## Elliptic flow

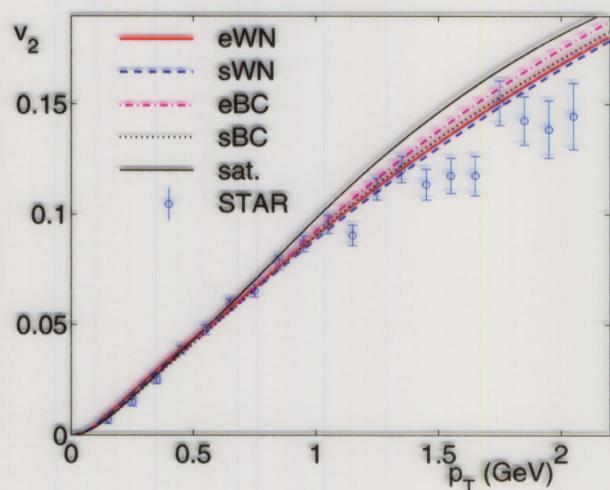
STAR-collaboration, K.H. Ackermann et al., Phys. Rev. Lett. 86 (2001) 402

$$v_2(p_t; b) = \frac{\int d\phi \cos(2\phi) \frac{dN}{dy d\phi p_t dp_t}(p_t, \phi; b)}{\int d\phi \frac{dN}{dy d\phi p_t dp_t}(p_t, \phi; b)}$$

over centrality



over momentum



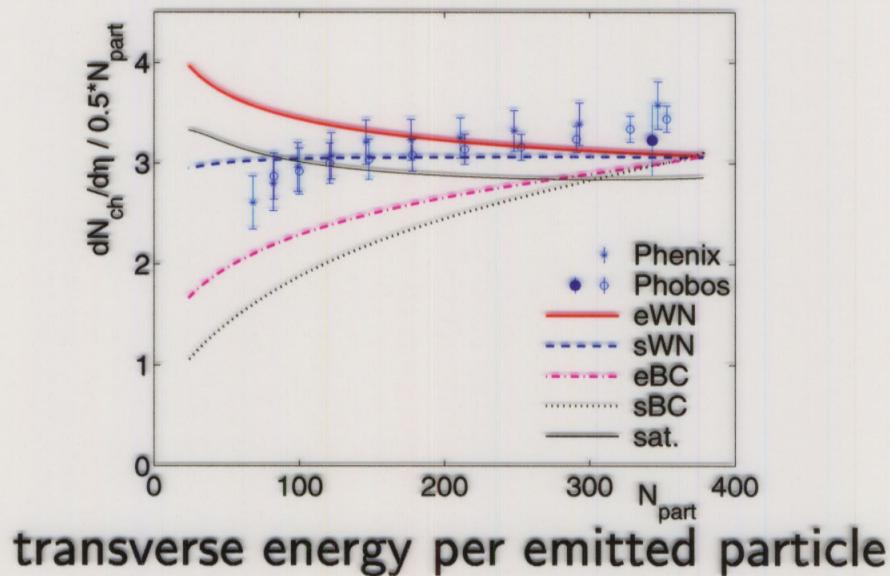
→ hydrodynamics is in good agreement with the data at central and semicentral collisions ( $b < 7 - 8$  fm) and transverse momenta up to  $p_T < 1.5 - 2.0$  GeV.

Deviations are due to lack of thermalization in peripheral collisions ('free streaming' → reduction of initial spacial anisotropy) and for high  $p_T$  particles (escape without equilibration).

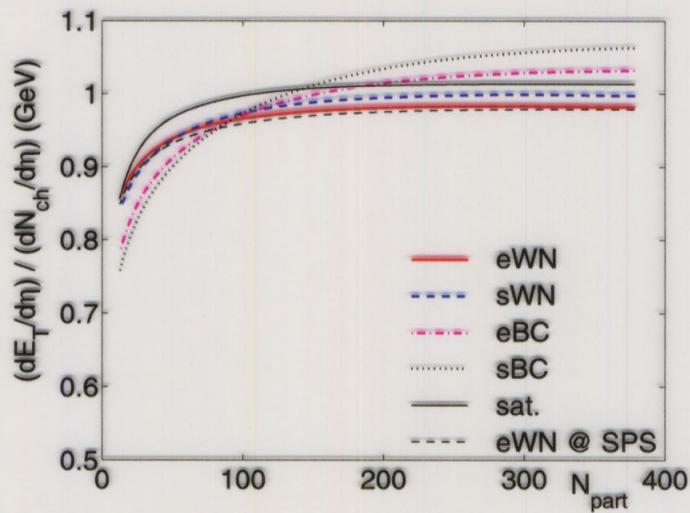
## Multiplicities and transverse energy

PHENIX-collaboration, K. Adcox et al., Phys. Rev. Lett. 86 (2001) 3500  
 G. Roland for the PHOBOS-collaboration at QM 2001

particle yield per participant pair



transverse energy per emitted particle

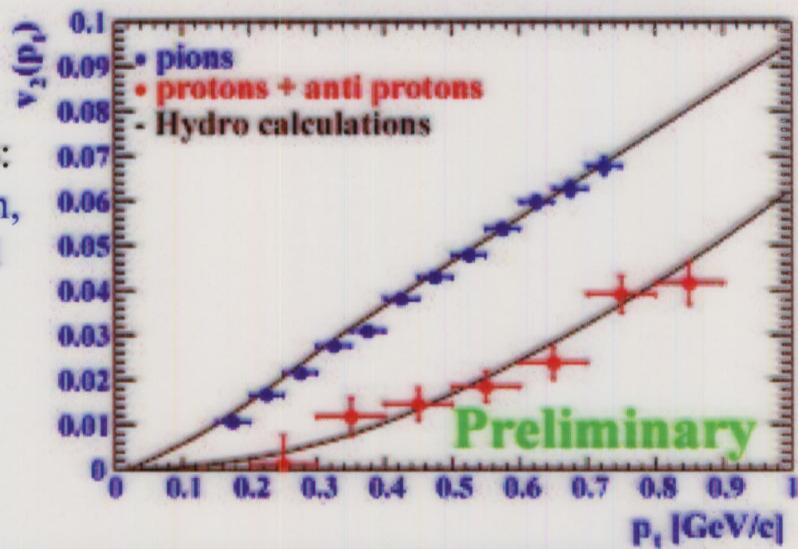


## Elliptic flow for different particle species



### A Hydro view of the world

- Hydro calculations:  
P. Huovinen,  
P. Kolb and  
U. Heinz



1/17/2001

Raimond Snellings, Quark Matter 2001

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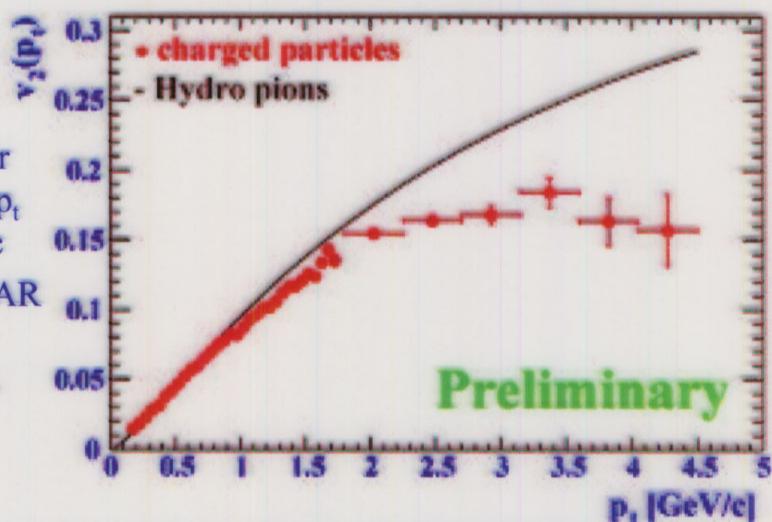
- Pions and protons in agreement with hydrodynamic results
- Higher mass of the particles under investigation lead to a more gradual rise of  $v_2(p_T)$

## Elliptic flow at high $p_T$

### Charged particle anisotropy $0 < p_t < 4.5 \text{ GeV}/c$



- Only statistical errors
- Systematic error 10% - 20% for  $p_t = 2 - 4.5 \text{ GeV}/c$
- More in the STAR high-pt talk (James Dunlop, PS2, this afternoon)



1/17/2001

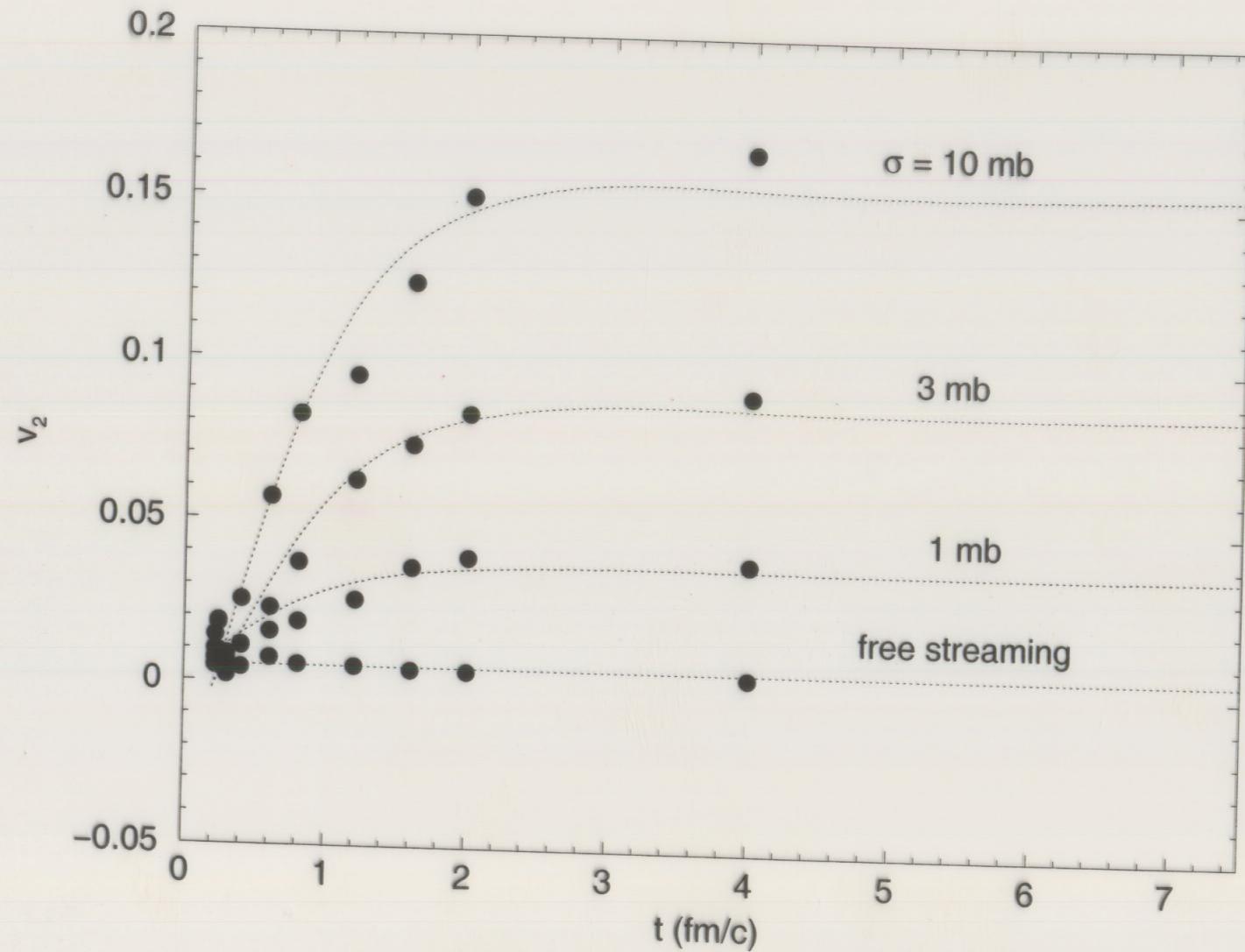
Raimond Snellings, Quark Matter 2001

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- Insufficient equilibration of high  $p_T$  particles
- Elliptic flow results from different pathlengths and energy loss (jet quenching)

X.N.Wang, nucl-th/0009019

*Elliptic flow requires rescattering:*



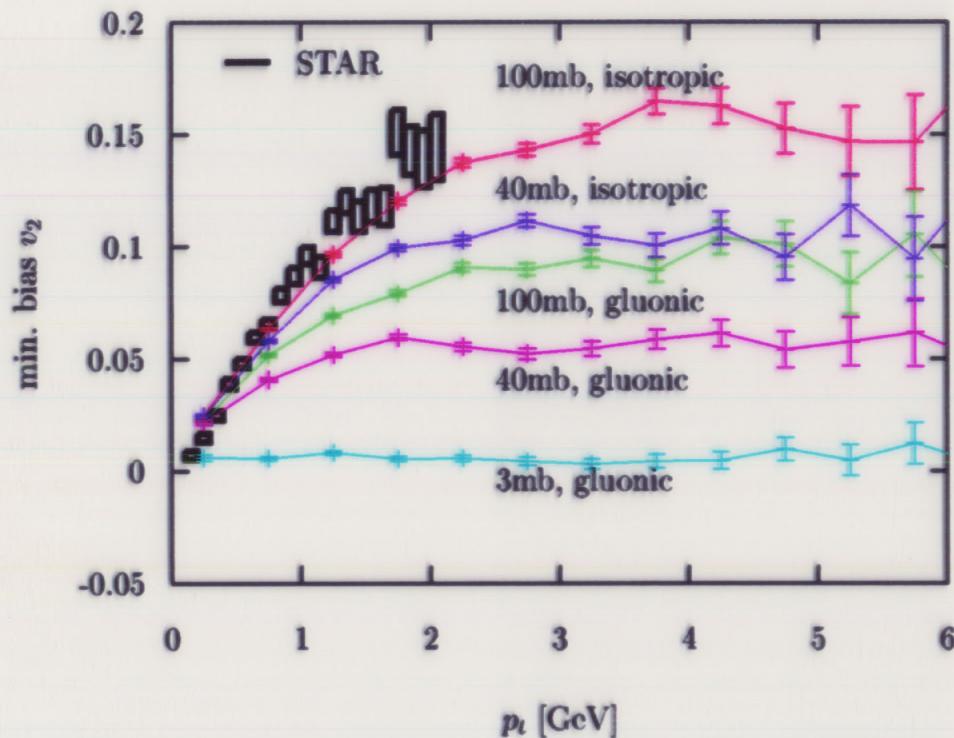
B.Zhang, M.Gyulassy, C.M.Ko, PLB 455 (1999) 45

In fact, a lot of rescattering!

$\approx 30 \times \sigma_{QCD}$   
 $\approx 10$  times  $\sigma_{QCD}$ !

## Minimum bias v2

MPC Au+Au,  $dN/d\eta_{cent} = 210$  (HIJING, 130A GeV)



Simple estimate:

$$v_2^{minbias} = \frac{2\pi}{\pi b_{max}^2} \int_0^{b_{max}} v_2(b) b db$$

$b_{max}$  not known → take 12fm

- $v_2$  grows with  $p_t$  until  $\sim 2 - 3$  GeV, then saturates
- data supports: HIJING  $dN/dy_{cent} = 210$ ,  $\sigma = 100\text{mb}$  isotropic, or EKRT  $dN/dy_{cent} = 1000$ ,  $21\text{mb}$  isotropic
- also possible with gluonic but needs higher cross sections or densities  
NOTE: 3mb gluonic requires  $dN/dy > 7000$  (!)

## Why is this so interesting?

- Initial momentum distribution is *locally isotropic*  
→  $v_2^{\text{init}} = 0$  even if  $\langle p_{\perp}^2 \rangle(\vec{r})$  initially anisotropic in  $\vec{r}$ .
- $v_2 \neq 0$  requires "rescattering".
- $v_2 \neq 0$  also requires spatial anisotropy  $\varepsilon_x$ .  
 $\varepsilon_x$  is diluted by free-streaming:

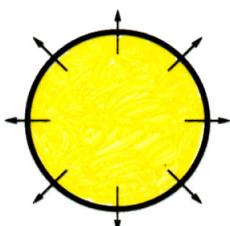
$$\frac{\varepsilon_x(t_0 + \delta\tau)}{\varepsilon_x(t_0)} = \frac{1}{1 + \frac{(c\delta\tau)^2}{R^2(1+\delta^2)}}$$

In Pb+Pb  $\Rightarrow b = 7 \text{ fm}$ ,  $\delta\tau = \begin{cases} 1 \text{ fm/c} \\ 2 \text{ fm/c} \end{cases}$  dilutes  $\varepsilon_x$  by  $\begin{cases} 10\% \\ 25\% \end{cases}$

- $v_2$  must be built up early
- For given  $\varepsilon_x$ , ideal (non-viscous) hydrodynamics gives largest possible  $v_2$  response. For  $b \lesssim 7 \text{ fm}$  and  $p_{\perp} \lesssim 1.5 - 2 \text{ GeV}$ , RHIC data saturate this upper limit!
- data require very strong rescattering and ≈ local thermalization ( $T^{\mu\nu} \approx T_{\text{ideal fluid}}^{\mu\nu}$ ) at a very early stage! How?? → next talk
- elliptic flow is self-quenching  
→ sensitive to EOS before hadronisation.

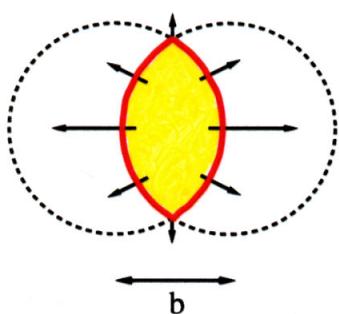
## Transverse Flow Patterns

### Radial flow:



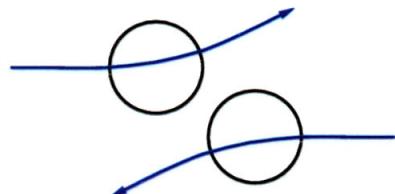
- Only type of transverse flow in  $b = 0, A = B$  collisions (*Aspherical*)
- Integrates pressure history over complete expansion stage

### Anisotropic flow:



- from deformed initial overlap region
- peaks at  $y = 0$
- anisotropic flow reduces spatial deformation, → shuts itself off
- more weight towards early stage of expansion (H. Sorge)

### Directed transverse flow:



- only in  $b \neq 0$  collisions
- probes the earliest collision stages (pre-equilibrium)